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On the nature of the intermittent pulsar PSR B1931+24

N. Rea,^{1,2★} M. Kramer,³ L. Stella,⁴ P. G. Jonker,^{2,5} C. G. Bassa,² P. J. Groot,⁶
G. L. Israel,⁴ M. Méndez,⁷ A. Possenti⁸ and A. Lyne³

¹University of Amsterdam, Astronomical Institute ‘Anton Pannekoek’, Kruislaan 403, 1098 SJ, Amsterdam, the Netherlands

²SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA, Utrecht, the Netherlands

³Jodrell Bank Observatory, University of Manchester, Macclesfield SK11 9DL

⁴INAF–Astronomical Observatory of Rome, via Frascati 33, 00040, Monteporzio Catone (RM), Italy

⁵Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

⁶Department of Astrophysics, Radboud University Nijmegen, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands

⁷Kapteyn Astronomical Institute, Groningen University, 9700 AV, Groningen, the Netherlands

⁸INAF–Astronomical Observatory of Cagliari, Poggio dei Pini, Strada 54, 09012 Capoterra (CA), Italy

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ABSTRACT

PSR B1931+24 is the first intermittent radio pulsar discovered to date, characterized by a 0.8-s pulsation, which turns on and off quasi-periodically every ~ 35 d, with a duty cycle of ~ 10 per cent. Here, we present X-ray and optical observations of PSR B1931+24 performed with the *Chandra X-ray Observatory* and the Isaac Newton Telescope, respectively. Simultaneous monitoring from the Jodrell Bank Observatory showed that this intermittent pulsar was in the radio-on phase during our observations. We do not find any X-ray or optical counterpart to PSR B1931+24, translating into an upper limit of $\sim 2 \times 10^{31}$ erg s^{−1} on the X-ray luminosity, and of $g' > 22.6$ on the optical magnitude. If the pulsar is isolated, these limits cannot constrain the dim X-ray and optical emission expected for a pulsar of this age (~ 1.6 Myr). We discuss the possibility that the quasi-periodic intermittent behaviour of PSR B1931+24 is a result of the presence of a low-mass companion star or gaseous planet, tight with the pulsar in an eccentric orbit. In order to constrain the parameters of this putative binary system, we re-analysed the pulsar radio timing residuals. We found that (if indeed hosted in a binary system) PSR B1931+24 should have a very low-mass companion and an orbit of low inclination.

Key words: pulsars: general – pulsars: individual: PSR B1931+24.

1 INTRODUCTION

A long-term radio monitoring study of the ~ 813 -ms radio pulsar PSR B1931+24 (Stokes et al. 1985; Hobbs et al. 2004) has revealed the peculiar intermittent behaviour of this pulsar (Kramer et al. 2006). PSR B1931+24 is (so far) a unique system: it shows an active radio emission phase lasting between 5–10 d (radio-on phase, hereafter), which suddenly (in less than 10 s) switches off, and the pulsar remains undetectable for the following 25–35 d (radio-off phase, hereafter). This pattern repeats quasi-periodically, and has been monitored for the past seven years (Kramer et al. 2006). Another peculiar property of PSR B1931+24 is its spin-down behaviour. Remarkably, the pulsar rotation slows down considerably faster (by about 50 per cent) when the pulsar is in the radio-on phase, with a frequency derivative changing from $\dot{\nu}_{\text{on}} = -(16.30 \pm 0.04) \times 10^{-15}$ s^{−2} to $\dot{\nu}_{\text{off}} = -(10.80 \pm 0.02) \times 10^{-15}$ s^{−2} across the two phases.

From the radio observations, typical pulsar characteristics have been derived (see table 1 in Kramer et al. 2006): an estimate of the dipolar magnetic field ($B \sim 2.6 \times 10^{12}$ G), the characteristic age ($\tau_c \sim 1.6$ Myr) and the dispersion measure ($DM = 106.03 \pm 0.06$ cm^{−3} pc). The latter has given a rough estimate of the pulsar distance of ~ 4.6 kpc using the NE2001 model for the free electron distribution in the Galaxy (Cordes & Lazio 2002). Kramer et al. (2006) have interpreted the peculiar spin-down properties of this pulsar in terms of a transient plasma flow in the magnetosphere, causing the quenching and reignition of the radio emission. In particular, an increase of the magnetospheric current flow during the radio-on phase can provide an additional braking torque on the neutron star. From the observed variations in the pulsar spin-down, they have shown that the pulsar magnetospheric electron density is consistent with the Goldreich–Julian density (Goldreich & Julian 1969). This interpretation can successfully explain the variable neutron star torque, but still fails to explain what causes the changes in the magnetospheric plasma flow, especially if in a quasi-periodic fashion. To date, this periodicity of the radio-on and radio-off recurrence is difficult to explain in any scenario considering an isolated

★E-mail: nrea@science.uva.nl

Table 1. Parameters derived from the radio timing analysis described in Section 4. Errors are at 1 σ confidence level.

Parameter	Value
RA (J2000)	19:33:37.88(5)
Dec. (J2000)	24:36:40(1.5)
Epoch	52281.296676
ν (Hz)	1.22896706877(3)
$\dot{\nu}$ (10^{-15} s $^{-2}$)	−12.1501(4)
$\ddot{\nu}$ (10^{-25} s $^{-3}$)	−2.0(2)
Dispersion measure (cm $^{-3}$ pc)	106.03(6)

pulsar. As Kramer et al. (2006) have pointed out, the short shut-off time of less than 10 s, and the stable pulse profile, rule out possible scenarios such as precession of the neutron star. However, the long radio-off phase is in contrast with typical nulling time-scales of radio pulsars, exceeding these by almost five orders of magnitude.

Cordes & Shannon (2008) studied the possibility that PSR B1931+24 might be in a binary system with a large asteroid, surrounded by a disk of small asteroids, moving in a ~ 40 -d eccentric orbit around the pulsar. This scenario suggests that the interaction between the pulsar magnetosphere and the asteroid could be responsible for both the torque change and the intermittent radio activity of PSR B1931+24. Recently, Zhang, Gil & Dyks (2007) have proposed that intermittent pulsars are old isolated neutron stars which have entered (or are about to enter) the so-called ‘death valley’ (Chen & Ruderman 1993), where the polar cap voltage of the pulsar is not sufficient to power the pair production process. However, this scenario still fails to account for the quasi-periodic pulsed emission of PSR B1931+24.

Here we report on X-ray (Section 2) and optical (Section 3) observations of PSR B1931+24 taken with the *Chandra X-ray Observatory* and the Isaac Newton Telescope. Furthermore, in Section 4 we derive constraints on possible orbital parameters and companion mass by studying the radio timing residuals. In Sections 5 and 6, we discuss our results and investigate in detail the possibility that PSR B1931+24 resides in a binary system with a ~ 35 -d orbital period and a low-mass companion star or a planet.

2 X-RAY OBSERVATION

The *Chandra* Advanced CCD Imaging Spectrometer (ACIS) observed PSR B1931+24 on 2006 July 20, for an on-source exposure time of ~ 9.7 ks. The target position was placed in the standard back-illuminated ACIS-S3 aimpoint, using the FAINT mode. We corrected the astrometry for any processing offset and we cleaned the image for hot pixels. Running CIAO CELLDETECT and WAVEDetect tools,¹ no X-ray sources were detected in the whole ACIS-S3 CCD, while four (unrelated) sources were detected in the other CCDs at $>5\sigma$ confidence level over the background. In particular, no photons were detected in a 1-arcsec radius around the radio position of PSR B1931+24 (see Table 1 for the RA and Dec.). We then obtained a 99 per cent upper limit on the source count rate of 4.74×10^{-4} count s $^{-1}$ (Gehrels 1986).

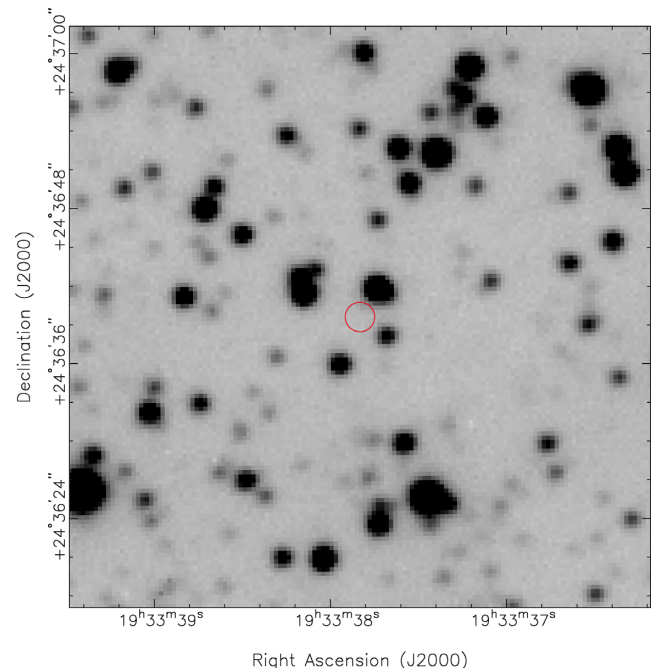
Assuming a conservative absorption value of $N_H = 8.3 \times 10^{21}$ cm $^{-2}$ (derived for the pulsar position from Dickey & Lockman 1990, and hence considering the whole Galactic N_H in that direction), and using the PIMMS calculator², we derived 99 per cent upper

limits on the 0.3–10 keV unabsorbed flux of 7×10^{-15} or 1.2×10^{-14} erg s $^{-1}$ cm $^{-2}$, assuming a blackbody ($kT = 0.3$ keV) or a power-law ($\Gamma = 2.5$) spectral decomposition, respectively. At 4.6 kpc, these fluxes translate into a 99 per cent upper limit on the 0.3–10 keV X-ray luminosities of 1.7×10^{31} and 3×10^{31} erg s $^{-1}$, depending on the assumed X-ray spectrum. However, note that the distance of 4.6 kpc, as inferred from the pulsar dispersion measure (Kramer et al. 2006), might have an uncertainty of a factor of 2 because of a ~ 30 per cent uncertainty in the Galactic electron density model (Cordes & Lazio 2002). Hence, more conservative upper limits on the luminosity would be four times larger than reported above.

3 OPTICAL OBSERVATIONS

We observed the field of PSR B1931+24 with the Isaac Newton Telescope located at the Roque de Los Muchachos Observatory in La Palma, for an exposure time of 10 min in three optical filters: g' , r' and i' (see Fig. 1 for the finding chart). No optical counterpart was detected within the radio pulsar position. We derived 5σ upper limits on the optical emission of PSR B1931+24 of $g' > 22.6$, $r' > 22.4$ and $i' > 22.2$ magnitudes. We inferred these optical upper limits from the magnitudes of the faintest object detected at 5σ confidence level in the same CCD as the pulsar position. For the astrometry, we used an 11×11 arcmin 2 subsection of the g' image, where we found 85 stars from the United States Naval Observatory (USNO) CCD Astrograph Catalog (UCAC2; Zacharias et al. 2004). We obtained an astrometric solution, fitting the zero-point position, scale and position angle; the final rms residuals were 0.13 arcsec in both in RA and Dec.

We inferred the reddening in the direction of PSR B1931+24 from N_H , which gave $A_V = 4.64$ (Predehl & Schmitt 1995). We then converted this value into an estimate of the reddening in the filter we actually used (Rieke & Lebofsky 1985; Schlegel, Finkbeiner & Davis 1998): $A_{g'} = 4.94$, $A_{r'} = 3.68$ and $A_{i'} = 2.83$. Considering

**Figure 1.** Finding chart of the i' field of PSR B1931+24. The circle is the uncertainty in the pulsar position as derived from radio timing (see Table 1).

¹ For details, refer to <http://asc.harvard.edu/ciao/>.

² For details, refer to <http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html>.

a distance of 4.6 kpc, we inferred upper limits on the source absolute magnitude of $g' > 4.35$, $r' > 5.2$ and $i' > 6.1$. From our upper limits of the absolute optical magnitudes, we can derive a rough range of stellar types for a putative counterpart. From $r' > 5.2$, which was the most constraining limit, we can exclude all giant and supergiant stars, and derive a spectral type later than a G8 star. Note that having assumed an absorption value of the whole Galactic N_H , any (more realistic) lower N_H values would result in stellar types much later than G8.

4 LIMITS ON THE ORBITAL PARAMETERS FROM THE RADIO TIMING

If PSR B1931+24 is in a binary system (e.g. as investigated in detail in Section 5), the motion of the pulsar around the system's centre of mass should leave a periodic signature in the remaining timing residuals. We searched for this signature in radio timing data spanning almost seven years (Kramer et al. 2006). We fitted the radio timing residuals with one spin-frequency derivative and a second derivative (values are given in Table 1). The latter was used to remove a cubic term due to long-term timing noise. In order to improve the position information, we removed the remaining timing noise by using the fit-wave method described by Hobbs et al. (2004), with a minimum period of 2 yr. The pre-fit-wave residuals were then analysed for periodicities caused by low-mass companions (with masses smaller than the pulsar mass, $M_c \ll M_p$), as described by Freire et al. (2003). As Fig. 2 shows, not surprisingly we detected a faint signal at a period of ~ 37 d. However, we believe this signal is consistent with a periodicity caused by the sampling of time-of-arrivals forced upon us by the quasi-periodic on-phases of the pulsar. We do not detect any other significant signal.

For a more general companion mass, we also performed the following analysis of the timing residuals. The peak-to-peak amplitude of the remaining timing residuals was $\Delta t_{\text{res}} \sim 2$ ms. From this, we placed limits on the corresponding orbital parameters by interpreting Δt_{res} as caused by a 'Roemer delay' (i.e. the light-travel time across the orbit; e.g. Lorimer & Kramer 2005). We then set

$$\Delta t_{\text{Roemer}} = x[(\cos E - e) \sin \omega + \sin E \sqrt{1 - e^2} \cos \omega]$$

equal to Δt_{res} . Here, E is the eccentric anomaly, e is the eccentricity and ω is the longitude of the periastron. Furthermore, $x = a_p \sin i/c$ is the projected semimajor axis measured in light seconds, which

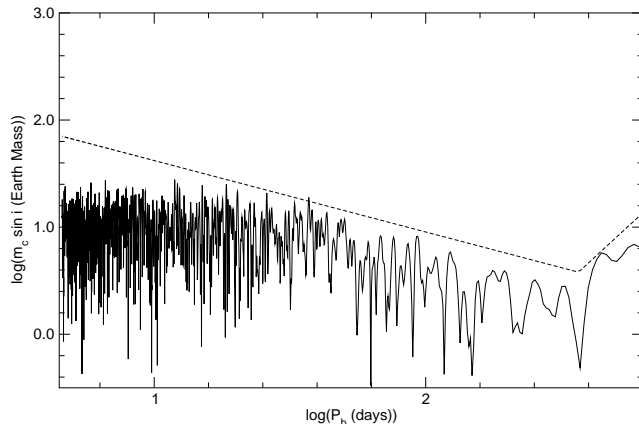


Figure 2. Lomb-scale spectrum of PSR B1931+24. The dashed line indicates a 99.99 per cent confidence level. A periodicity is detected at ~ 37 d, but see text for details.

is a function of $a_p = a_R M_c/(M_p + M_c)$, the semimajor axis of the orbit. i is the orbital inclination angle, c is the speed of light and a_R is the size of the relative orbit.

However, the relative orbit a_R , the orbital period and masses are related according to Kepler's third law

$$\frac{4\pi^2}{P_{\text{orb}}^2} \left(\frac{a_R}{c} \right)^3 = T_{\odot} (M_p + M_c),$$

with the masses measured in solar units and $T_{\odot} = GM_{\odot}/c^3 = 4.925490947 \mu\text{s}$. Assuming $P_{\text{orb}} \sim 35$ d and $M_p \sim 1.4 M_{\odot}$, we can derive an estimate for the orbital inclination angle as a function of the companion mass in the following way. For a given companion mass M_c , we performed Monte Carlo simulations, drawing possible values for E , ω and e from uniform distributions over $[0, 2\pi]$ and $[0, 1]$, respectively. Note that the distribution for the eccentricity is not expected to be uniform (i.e. it is likely to be skewed to small eccentricities), but for our purposes this assumption is sufficient as we were mostly interested in upper bounds for the inclination angle. For each companion mass, one million Monte Carlo runs were performed and the median and 95 per cent confidence limits were computed (see Fig. 2; the grey shadowed region is the allowed region at 95 per cent confidence level). Hence, for reasonable companion masses, the tight limit on a detectable periodicity in the timing residuals implies small orbital inclination angles (see also Section 6).

5 INVESTIGATING THE POSSIBLE BINARY NATURE OF PSR B1931+24

In this section we investigate the possibility that the peculiar characteristics of PSR B1931+24 can be explained by a low-mass star or a gaseous planet moving in an eccentric orbit around the pulsar (see also Section 4). This causes quasi-periodic intermittent behaviour, as well as the change in the spin-down characteristics of the pulsar, in two different ways, either (i) providing at the periastron passage the additional plasma needed in the Kramer et al. (2006) model, or (ii) accreting material on the pulsar magnetosphere and causing the transition between the radio pulsar and the propeller regime (for details, see Illarionov & Sunyaev 1975; Stella, White & Rosner 1986; Stella et al. 1994). In this section we discuss only the second possibility. The physics involved in the first possibility has been thoroughly investigated by Kramer et al. (2006), although without considering the wind of a companion as the source of the additional magnetospheric plasma during the radio-on phase (see also Section 6).

Here we define three important PSR B1931+24 radii, which will be used in the following:

the magnetospheric radius

$$R_m = 2 \times 10^7 \dot{M}_{15}^{-2/7} B_9^{4/7} M_{1.4}^{-1/7} R_6^{12/7} \\ \simeq 1.78 \times 10^9 \dot{M}_{15}^{-2/7} \text{ cm};$$

the corotation radius

$$R_{\text{cor}} = 0.12 \times 10^8 M_{1.4}^{1/3} P_{10}^{2/3} \simeq 2.25 \times 10^8 \text{ cm};$$

and the light cylinder radius

$$R_{\text{lc}} = 0.46 \times 10^8 P_{10} \simeq 3.74 \times 10^9 \text{ cm}.$$

These three radii represent, respectively, (i) the balance of the gravitational force and the ram pressure of the infalling material, (ii) the centrifugal barrier for the infalling material due to the pulsar rotation, and (iii) the place where the pulsar magnetic field lines

open such that their tangential velocity does not exceed the speed of light (Illarionov & Sunyaev 1975; Ruderman & Sutherland 1975).

We define the following: $B_9 = B_{\text{ns}}/10^9$ G is the neutron star magnetic field; P_{10} is the spin period in units of 10 ms; $\dot{M}_{15} = \dot{M}/10^{15} \text{ g s}^{-1}$ is the mass inflow rate toward the neutron star; $M_{1.4} = M_{\text{ns}}/1.4 M_{\odot}$ and $R_6 = R_{\text{ns}}/10^6$ cm are the mass and radius of the neutron star, hereafter assumed $M_{1.4} = R_6 = 1$. Note that, during the orbital motion, the only variable radius is $R_m \propto \dot{M}_{15}^{-2/7}$.

5.1 Radio pulsar is on

If the mass inflow rate from the putative companion star is very low, as might occur at the apastron of an eccentric orbit, the magnetosphere of the neutron star might be larger than the light cylinder and corotation radii ($R_m > R_{\text{lc}} > R_{\text{cor}}$).

As a result, the centrifugal barrier is closed, which means that incoming material from the companion star is prevented from falling towards the neutron star magnetosphere or surface. In this case, the neutron star might behave as a radio pulsar. The pulsar radiation pressure dominates over the ram pressure of the inflowing material, preventing the matter from penetrating towards the neutron star (Illarionov & Sunyaev 1975; Davies & Pringle 1981; Stella et al. 1994; Campana et al. 1998).

This occurs when the mass inflow rate (\dot{M}) is smaller than the limiting value

$$\dot{M}_{15, \text{radio-off}} = 5.4 \times 10^{-2} B_9^2 P_{10}^{-7/2} M_{1.4}^{-1/2} R_6^6 \simeq 0.075,$$

above which the radio pulsations would quench, even as rapidly as ~ 10 s.

It is worth noting that when $\dot{M} \sim \dot{M}_{15, \text{radio-off}}$, the radio pulsar emission is not in equilibrium (Illarionov & Sunyaev 1975; Shaham & Tavani 1991), depending on the stability of the mass inflow rate; sporadic variability of the radio-on duration of PSR B1931+24 might take place, as indeed has been observed (Kramer et al. 2006). Furthermore, during the radio-on phase, variations in the pulsar dispersion measure as a function of the orbital phase are expected. Unfortunately, the observations were performed at one frequency, making it impossible to put a meaningful limit on the dispersion measure variability (see also Kramer et al. 2006).

5.2 Radio pulsar is off

If the mass inflow rate starts to increase (e.g. approaching periastron), we expect a correlated decrease of the magnetospheric radius, which eventually becomes smaller than the light cylinder radius ($R_{\text{lc}} > R_m > R_{\text{cor}}$). This occurs when the mass inflow rate towards the neutron star becomes larger than the limiting value $\dot{M}_{15, \text{radio-off}}$. At this point the pulsar radiation pressure is overcome by the ram pressure of the infalling material quenching the radio pulsar mechanism. Different regimes are then allowed at this stage. If R_m remains larger than R_{cor} , which means $\dot{M}_{15, \text{radio-off}} < \dot{M} < \dot{M}_{15, \text{acc}}$, with

$$\dot{M}_{15, \text{acc}} = 5.97 B_9^2 P_{10}^{-7/3} M_{1.4}^{-5/3} R_6^6 \simeq 1.4 \times 10^3,$$

then the magnetosphere of the neutron star still rotates in a super-Keplerian motion, and the inflowing material might either accumulate outside the magnetospheric boundary or be swept away by the magnetospheric drag. This is called the ‘propeller’ regime (Pringle & Rees 1972; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Stella et al. 1986).

Given the upper limits we have derived for the possible companion star (see Sections 3 and 4), there is only a very small chance that \dot{M} , because of the wind loss of the companion, overcomes $\dot{M}_{15, \text{acc}}$.

We then consider hereafter only the possibility that the radio-off phase is driven by the propeller regime, excluding the surface accretion scenario.

When the radio pulsations are quenched, the spin-down behaviour of the pulsar is no longer driven by the magnetic dipolar loss as it was previously. What happens to the pulsar spin-down during the propeller regime is still controversial, and requires detailed hydrodynamic simulations (Romanova et al. 2003). Depending on which type of instability and shock takes place on the pulsar magnetosphere, the spin-down rate might either increase further or be reduced by the angular momentum transferred by the infalling material to the magnetosphere.

In the PSR B1931+24 case, it is clear that the infalling material should provide a certain rotational energy in order to make the pulsar slow down less efficiently during the radio-off phase, changing the spin-down of the neutron star by $\Delta\dot{\nu} = \dot{\nu}_{\text{on}} - \dot{\nu}_{\text{off}} = -5.5 \pm 0.4 \times 10^{-15} \text{ Hz s}^{-1}$, which converted into energy corresponds to $\Delta\dot{E} \simeq 4\pi^2 I \nu \Delta\dot{\nu} \simeq 2.6 \times 10^{30} \text{ erg s}^{-1}$.

When the infalling matter reaches the neutron star magnetosphere, the source is expected to emit in the X-ray band with a minimum luminosity of

$$L_{\text{radio-off}} = 7 \times 10^{31} B_9^2 P_{10}^{-9/2} M_{1.4}^{1/2} R_6^6 \simeq 0.12 \times 10^{31} \text{ erg s}^{-1},$$

and a maximum luminosity related to the maximum wind loss we expect from the inferred companion type. For a stellar type later than G8, we expect the X-ray luminosity of the system in the radio-off phase to be between $1.2 \times 10^{30} - 1.6 \times 10^{32} \text{ erg s}^{-1}$.

After the periastron passage, the low-mass companion star moves towards apastron, the magnetospheric boundary expands because of the decreasing mass inflow rate, the centrifugal barrier closes and the radio pulsar mechanism can resume again.

6 DISCUSSION

The upper limits we have derived from these X-ray and optical observations of PSR B1931+24 during the radio-on phase are not enough to detect the typical X-ray luminosity ($< 10^{29} \text{ erg s}^{-1}$; Becker & Trümper 1997) and optical magnitude ($V > 28$; Mignani et al. 2007) of an isolated pulsar of ~ 1.6 Myr, such as PSR B1931+24.

However, if the pulsar is hosted in a binary system, we derived tight constraints on the putative companion and its orbital parameters. We constrained the companion to be a low-mass star later than a G8 type star or a gaseous planet. For an orbital inclination of 0° , the companion would have a mass of $M_c < 0.01 M_{\odot}$, while with a smaller inclination of $0^\circ 01'$, the companion mass is allowed to be $M_c < 0.1 M_{\odot}$ (all at 95 per cent confidence level; see Fig. 3).

In the binary scenario (see Section 5), the pulsar intermittence can be explained by the transition between the radio pulsar regime and the propeller regime during the orbital motion. The X-ray upper limits we have derived are unfortunately relative to the radio pulsar dominated regime (note that the source was radio-on during the observations), and not to the propeller regime when the source can be bright in the X-ray because of the accretion of matter on to the pulsar magnetosphere. Our *Chandra* observation was in fact aimed at detecting a possible X-ray emission from PSR B1931+24 during its radio-off phase. Unfortunately, the relatively uncertain duration of both phases (the radio-on phase rarely might be longer than the average duration), and the relatively large error (\sim a few days) on the putative periastron passage, made us carry out the observation during the radio-on phase of the pulsar.

Note that the insufficient flux detection limit of current and past X-ray surveys and monitoring programmes (e.g. *ROSAT* and the

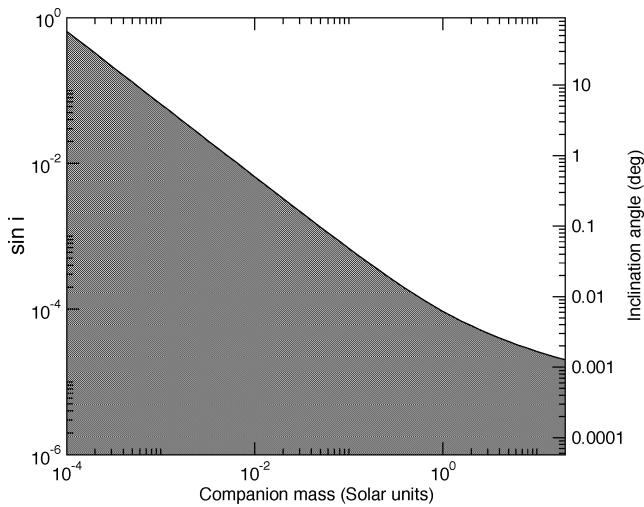


Figure 3. Limits on the orbital inclination angle as a function of the companion mass as derived from the pulsar radio timing. For each companion mass, one million Monte Carlo runs were performed, and the median and 95 per cent confidence limits were computed. The grey shadowed region is the allowed region at 95 per cent confidence level.

Rossi X-Ray Timing Explorer All-Sky Monitor) do not make the non-detection of an X-ray counterpart in previous X-ray surveys at all constraining.

Although very successful in explaining the intermittence, the quasi-periodicity and the torque variations of PSR B1931+24, this binary scenario still presents several unsolved issues. One issue of this scenario, and to some extent also to the ‘asteroid’ model (Cordes & Shannon 2008), is the very small orbital inclinations required by the radio timing studies (Section 4 and Fig. 3). For a random distribution of inclination angles, the probability of observing a system at an angle less than a value i_0 is $p(i < i_0) = 1 - \cos i_0$. Considering the favourable case of an angle of 15° (a gaseous planet; see Fig. 3), the probability of observing such a system is $p(i < 15^\circ) = 3.4$ per cent. A chance of 3.4 per cent is not very high, although still worth considering.

Another issue concerns the accretion rate from the companion. Can the accretion from the low wind loss of such a small-mass star or gaseous planet be high enough to switch the pulsar from the radio emitting regime to the propeller regime? Typical wind rates for a K0 star, for example, are insufficient to produce the limiting value of $\dot{M}_{15, \text{radio-off}}$ by \sim two orders of magnitude. This problem might be partially (but not totally) alleviated by taking into account the irradiation process (Podsiadlowski 1991; D’Antona & Ergma 1993). In particular, a low-mass star irradiated by the radio pulsar is expected to expand even if the radiation bath is not particularly extreme, and the wind of the star to increase substantially. However, the irradiation process cannot be dominant on the stellar wind from a G8 to K0 star, mainly because of the relatively low rotational energy of PSR B1931+24 with respect to the surface temperature of the companion star [$L_{\text{irr}} = f \dot{E}_{\text{rot}} (R_s/2a_p)^2$, where R_s is the radius of the companion star]. For lower-mass stars or considering a gaseous planet orbiting around the pulsar, this process might instead have a substantial role, and might produce strong winds towards the pulsar while at periastron.

If the weak stellar wind from the low-mass companion star is insufficient to drive the radio pulsar in the propeller regime, it is instead strong enough to provide the amount of plasma needed to

produce the spin-down change in the scenario proposed by Kramer et al. (2006). Note that, in this picture, at the periastron passage we expect the radio-on phase, while in the propeller scenario it is expected at the apastron of the orbit. However, while the propeller scenario naturally explains the quenching of the radio emission, in this picture the radio quenching still remains puzzling. We would in fact expect to see the pulsar all the time, although with two different spin-down behaviours.

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